

Planets in evolved binary systems

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ABSTRACT

Exoplanets are typically thought to form in protoplanetary disks left over from protostellar disk of their newly formed host star. However, additional planetary formation and evolution routes may exist in old evolved binary systems. Here we discuss the implications of binary stellar evolution on planetary systems in such environments. In these binary systems stellar evolution could lead to the formation of symbiotic stars, where mass is lost from one star and could be transferred to its binary companion, and may form an accretion disk around it. This raises the possibility that such a disk could provide the necessary environment for the formation of a new, second generation of planets in both circumstellar or circumbinary configurations. Pre-existing first generation planets surviving the post-MS evolution of such systems would be dynamically effected by the mass loss in the systems and may also interact with the newly formed disk. Such planets and/or planetesimals may also serve as seeds for the formation of the second generation planets, and/or interact with them, possibly forming atypical planetary systems. Second generation planetary systems should be typically found in white dwarf binary systems, and may show various observational signatures. Most notably, second generation planets could form in environment which are inaccessible, or less favorable, for first generation planets. The orbital phase space available for the second generation planets could be forbidden (in terms of the system stability) to first generation planets in the pre-evolved progenitor binaries. In addition planets could form in metal poor environments such as globular clusters and/or in double compact object binaries. Observations of exo-planets in such forbidden or unfavorable regions could possibly serve to uniquely identify their second generation character. Finally, we point out a few observed candidate second generation planetary systems, including Gl 86, HD 27442 and all of the currently observed circumbinary planet candidates. A second generation origin for these systems could naturally explain their unique configurations.

Subject headings: Planets – binary stars – stellar evolution – white dwarfs

1. Introduction

Currently, over 400 extra-Solar planetary systems have been found; most of them around main sequence stars, with a few tens found in wide binary systems. Typically, such planets are thought to form in a protoplanetary disk left over following the central star formation in a protostellar disk (e.g. Armitage 2007, for a recent review). Several studies explored the later effects of stellar evolution on the survival and dynamics of planets around an evolving star (Debes & Sigurdsson 2002; Villaver & Livio 2007) or the possible formation of planets around neutron stars (NSs; see Phillips & Thorsett (1994); Podsiadlowski (1995) for reviews). Others studied the formation and stability of planets in binary systems (see Haghighipour 2009, for a review). Here we focus on the implications of stellar evolution *in binaries* on the formation and growth of planets. More detailed discussion of these issues could be found in (Perets 2010; Perets & Kenyon 2010a,b).

One of the most likely outcomes of stellar evolution in binaries is mass transfer from an evolved donor star [which later becomes a compact object; a white dwarf (WD), NS or a black hole (BH); here we mostly focus on low mass stars which evolve to become WDs] to its binary companion. If the binary separation is not too large, this process could result in the formation of an accretion disk containing a non-negligible amount of mass around the companion. Such a disk could resemble in many ways a protoplanetary disk, and could possibly produce a second generation of planets and/or debris disks around old stars. In addition, the renewed supply of material to a pre-existing ('first generation') planetary system (if such exists after surviving the post-MS evolution of the host star), is likely to have major effects on this system, possibly leading to the regrowth/rejuvenation of the planets and planetesimals in the system as well as possibly introducing a second epoch of planetary migration.

The later evolution of evolved binaries could, in some cases, even lead to a third generation of planet formation in the system. When the previously accreting star (the lower mass star in the pre-evolved system) goes through its stellar evolution phase, it too can expand to become a mass donor to its now compact object companion. A new disk of material then forms around the compact object and planet formation may occur again, this time around the compact object (see also Beer et al. 2004 which tries to explain the formation the pulsar planet system PSR B1620-26).

In the following we discuss the role of binary stellar evolution in the formation of a second and third generation of planets in evolving binary systems (a schematic overview of this scenario is given in Fig. 1) and the interaction of accretion disks with pre-existing planets. We begin by discussing the conditions for the formation of a second generation protoplanetary disk and its properties (§2). We then explore the role of such disks in the

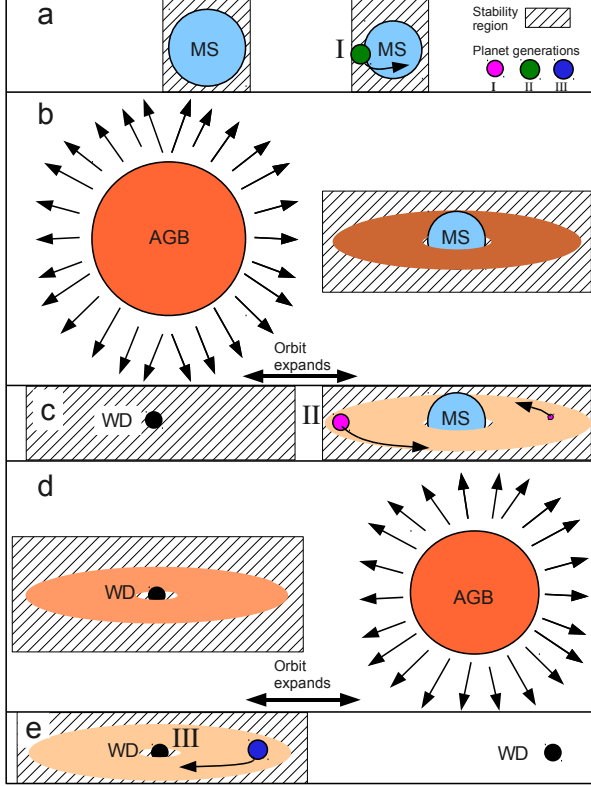


Fig. 1.— Second (and third) generation planet formation. The various stages of second generation planet formation are shown schematically. (a) The initial configuration: a binary MS system, possibly having a first generation (I) circumstellar planet around the lower mass on an allowed (stable) orbit. (b) The higher mass stars evolves to the AGB phase, and sheds material which is accreted on the secondary, and forms a protoplanetary disk. The binary orbit expands, and the allowed stability region expands with it. The existing first generation planet may or may not survive this stage (see text). (c) Second generation debris disk and planets are formed, in regions previously forbidden for planet formation (in the pre-evolved system; panel a). (d) The secondary evolves off the MS, and sheds material to its now WD companion. A protoplanetary disk forms. The binary orbit and the planetary allowed region (around the WD) further expand. Second generation planets may or may not survive this stage (see text). (e) Third generation debris disk and planets are formed around the WD, in regions previously forbidden for planet formation (in the pre-evolved system; panel a).

formation of new planets (§3), their effects on pre-existing planetary systems (§4), and on the formation of planets around compact objects (§5). We then review the observational expectations for such second generation planetary systems as suggested from our discussion (§6). Finally we suggest several planetary systems as being candidate second generation planetary systems (§7) and then conclude (§8).

2. Second generation protoplanetary disks

The first stage in planet formation would be setting the initial conditions of the protoplanetary disk in which the planets could form. We therefore first try to understand whether appropriate disks could be produced following a mass transfer epoch during the stellar evolution of a binary. Studies of planet formation in binary stars suggest that the binary separation should be large, in order for planets to be formed and produce a planetary system around one of the binary stellar components (see Haghighipour 2009, for a review). This is also consistent with the observational picture in which the smallest separations for a planets hosting binaries are of the order of ~ 20 AU (Eggenberger et al. 2004). We therefore mostly focus on relatively wide wind accreting binaries in §2.1. Nevertheless, mass transfer in close binaries could produce circumbinary disks of material, possibly serving as an environment for formation of circumbinary planets, we briefly discuss this latter more complicated possibility in §2.2. We then shortly also discuss the composition of second generation disks.

2.1. Circumstellar disks formed in wind accreting wide binaries

In order to understand the conditions for the formation of circumstellar disks from wind accreted material, we follow Soker & Rappaport (2000). For a disk to form around a star (or compact object), one requires that that $j_a > j_2$, where j_a is the specific angular momentum of the accreted material, and $j_2 = (GM_2 R_2)^{1/2}$ is the specific angular momentum of a particle in a Keplerian orbit at the equator of the accreting star of radius R_2 . For typical values for a MS accretor and a mass-losing terminal AGB star they find the following condition for the formation of a disk

$$1 < \frac{j_a}{j_2} \simeq 7.2 \left(\frac{\eta}{0.2} \right) \left(\frac{M_1 + M_2}{2.5 M_\odot} \right) \left(\frac{M_2}{M_\odot} \right)^{3/2} \times \left(\frac{R_2}{R_\odot} \right)^{-1/2} \left(\frac{a}{10 \text{ AU}} \right)^{-3/2} \left(\frac{v_r}{15 \text{ km s}^{-1}} \right)^{-4} \quad (1)$$

where M_1 and M_2 are the masses of the donor and accreting stars, respectively. R_2 is the radius of the accreting star, and a is the semi-major axis of the binary. v_r is the relative velocity of the wind and the accretor, η is the parameter indicating the reduction in the specific angular momentum of the accreted gas caused by the increase in the cross-section for accretion from the low-density side (where $\eta \sim 0.1$ and $\eta \sim 0.3$ for isothermal and adiabatic flows, respectively; Livio et al. 1986), and where they approximate v_r to be a constant equal to 15 km s^{-1} . From this condition, it turns out that a disk around a main sequence star with $R_2 \sim R_\odot$, could be formed up to orbital separations of $a \sim 37 \text{ AU}$; for a WD accretor an orbital separation of even $a \sim 60 \text{ AU}$ is still possible. Note, however, the strong dependence on the wind velocity, which could produce a few times wider or shorter accreting systems for the range of $5 - 20 \text{ km s}^{-1}$ possible in these winds (e.g. Kenyon 1986; Habing 1996). Since the peak of the typical binary separation distribution is at this separation range (Duquennoy & Mayor 1991), we conclude that a non negligible fraction of all binaries should evolve to form accretion disks during their evolution.

AGB stars can lose a large fraction of their mass to their companion. Given a simple estimate, a fraction of $(R_a/2a)^2$ of the mass, where R_a is the radius of the Bondi-Hoyle accretion cylinder (i.e. gas having impact parameter $b < R_a = 2GM_2/v_r^2$), is transferred to the companion accretion disk. The total mass transferred from the AGB could therefore range between $\sim 0.1 - 20$ percents of the total mass lost from the AGB star (for wind velocities of $5 - 15 \text{ km s}^{-1}$ and separation between $10 - 40 \text{ AU}$; with the smallest separation and largest mass corresponding to the largest fraction and vice verse). The total mass going through the accretion disk could therefore range between $\sim 10^{-3} - 1 M_\odot$ (for the range of parameters and donor stars masses of $1 - 7 M_\odot$; in principle higher mass stars could contribute even more, however these would also result in supernova explosions with further implications which are beyond the scope of this paper). Accordingly the accretion rate on to the star could have a wide range, with rates as high as $\sim 10^{-4} M_\odot \text{ yr}^{-1}$ and as low as 10^{-7} yr^{-1} (See also Winters et al. 2000, for detailed discussion of mass loss rates). Red giants before the AGB stage lose mass at slower rates, with $\dot{M} \sim 10^{-10} - 10^{-8} M_\odot \text{ yr}^{-1}$ (Kenyon 1986). Such a range of accretion rates at the different stellar evolutionary stages is comparable to the range expected and observed in regular (‘first generation’) protoplanetary disks at different stages of their evolution (e.g. Alexander 2008, for a review). We note that numerical simulations of wind accretion give very similar results, consistent with the simple estimates discussed here (de Val-Borro et al. 2009). When no accumulation of material is assumed. the simulations show the formation of a stable steady state accretion disk with a total mass of $\sim 10^{-4}$ of the stellar mass at 5 AU . Higher accretion rates/and or accumulation of material are likely to increase this even further. Moreover, typically ~ 5 percents of the mass lost from the AGB star goes through the disk in these simulations, again consistent

with the simple estimates given above, providing enough material for the build up of planets.

2.2. Circumbinary disks formed around evolved binaries

Formation of circumbinary disks in wide binaries is of less interest for the the formation of second generation planets. Dynamically stable configuration of disks and/or planets would require them to have very wide separations (a few times the binary orbits; Haghighipour 2009). Disks around wide binaries would have even wider configurations, at which regions planet formation is less likely to occur (Dodson-Robinson et al. 2009).

The evolution of close binaries could be quite complicated. Close binaries could evolve through a common envelope stage, which is currently poorly understood. Such binaries, and even wider binaries which do not go through a common envelope stage, but tidally interact, are likely to inspiral and form shorter period binaries during the binary post-MS evolution (see 3.1). Formation of circumbinary disks from the material lost from the evolving component of the binary, have hardly been discussed in the literature, and suggested models are highly uncertain (Akashi & Soker 2008, also Soker, private communication, 2010)). Nevertheless, the higher mass of the binary relative to the evolving AGB star, always provides a deeper gravitational potential than that of the AGB star. In such a configuration material from the slow AGB wind which escapes the AGB star potential would still be bound to the binary, and therefore fall back and accrete onto the binary. Indeed, many circumbinary disks are observed around evolved binary systems (see section 7).

Another possibility exists in which a third companion in a hierarchical triple (with masses $M_1 = m_1 + m_2$, for the close binary and M_2 for the distant third companion, and semi-major axis a_1 and a_2 for the inner and outer system, respectively) evolves and shed its material on the binary. This possibility is more similar to the case of the formation of a circumstellar disk in a binary, in which case Eq. 1 above could be applied. In this case the radius of the accreting star is replaced by the binary separation of the close binary, i.e. $R_2 \rightarrow a_1$ and the mass of the accretor is taken to be to be that of the close binary system etc.

2.3. Disks composition

AGB stars are thought to have a major contribution to the chemical enrichment of the galaxy (van den Hoek & Groenewegen 1997; Tosi 2007). Such stars could chemically pollute their surrounding and create an environment with higher metallicity in which later

generations of stars form as higher metallicity stars (see e.g. Tosi 2007, for a recent review). In addition, large amounts of dust are formed and later on ejected from the atmospheres of evolved stars and their winds (Gail et al. 2009; Gail 2009, and references therein). Given the high metallicity and dust abundances expected from, and observed in the ejecta of evolved stars, the accretion disk formed from such material is expected to be metal and dust rich. The composition of such disks may therefore serve as ideal environment for planet formation, as reflected in the correlation between the metallicity of stars and the frequency of exo-planetary systems around them (e.g. Fischer & Valenti 2005).

3. Second generation planets

Studies of first generation planet formation suggest that the accretion rates in regular protoplanetary disks, even in close binaries (Jang-Condell et al. 2008), could be very similar to those expected in accretion disks formed following mass transfer. The composition of such disks may be even more favorable for planet formation due to their increased metallicity. Observationally, first and second generation disks (formed from the protostellar disks of newly formed stars, and from mass transfer in binaries, respectively) seem to be very similar in appearance, raising the possibility of planet formation in these disks, as already mentioned in several studies (Jura & Turner 1998; Zuckerman et al. 2008; Melis et al. 2009). The lifetime of AGB stars is of the order of up to a few Myrs (e.g. Marigo & Girardi 2007), comparable to that of regular, first generation, protoplanetary disks. In view of the discussion above, it is quite plausible that new, second generation planets, could form in the appropriate timescales in second generation disks around relatively old stars, in much the same way as planets form in the protoplanetary disk of young stars. In the following we discuss the implications and evolution of such second generation planetary systems.

Although very similar, the environments in which second generation planets form has several differences from the protoplanetary environment of first generation planets. As mentioned above the composition of the disk material is likely to be more metal rich than typical protoplanetary disk, and these planets should all form and be observed in WD binaries (or other evolved binaries or compact objects such as NSs or BHs), with the youngest possibly already existing in post-AGB binaries. Both the binarity and disk composition properties of second generation planets may not be unique, and could be similar to those in which first generation planets form and evolve. Indeed many planets are found in binary systems or have metal rich host stars. Nevertheless, second generation planets form in much older systems than first generation ones and have a different source of material. Such differences could have important effects on the formation and evolution of second generation planets

which are also likely to be reflected in their observational signatures, as we now discuss.

Second generation planets should be exclusively found in binaries with compact objects (most likely WDs), including binaries in which both components are compact. A basic expectation would be that the fraction of planet hosting WD binary systems should differ from that in MS binary systems with similar dynamical properties. Moreover, double compact object binaries (WD-WD, WD-NS etc.) may show a larger frequency of planets than single compact objects¹.

Correlation between planetary companions and their host star metallicity could show a difference between WD binary systems and MS binary systems. This may be a weak signature, given that the host star itself may accrete metal rich material from the companion. Nevertheless, the latter case could be an advantage for targeting second planet searches, through looking for them around chemically peculiar stars in WD systems (e.g. Jeffries & Smalley 1996; Jorissen 1999; Bond et al. 2003). The high metallicity of second generation disks originate from the evolved star that produced them and need not be related to the metallicity of their larger scale environments. For this reason, second generation planets can form even in metal poor environments such as globular clusters, or more generally around metal poor stars. This possibility could be tested by searching for WD companions to planet hosting, but metal poor, stars (e.g. Santos et al. 2007). Reversing the argument, one can direct planet searches around metal poor stars (which typically do not find planets; Sozzetti et al. 2009) to look for them in binary systems composed of a metal poor star and a WD. Similarly, planet hosting stars in the metal poor environments of globular clusters are likely to be members of binary WD systems. Note, however, that given their formation in binaries, second generation planets are not expected to exist in the globular cluster cores, where dynamical interactions may destroy even relatively close binaries. Such second generation planetary systems should still be able to exist at the outskirts of globular clusters. Interestingly, the only planet found in a globular cluster (PSR B1620-26; Backer et al. 1993) is a circumbinary planet around a WD-NS binary, found in the outskirts of a globular cluster, as might be expected from our discussion (see section 7 for further discussion of this system).

The age of second generation planets, if could be measured, should be inconsistent with and much younger than their stellar host age (such implied inconsistencies could be

¹Planets around an evolving donor star could be engulfed by the star and be destroyed. We are not interested in comparing the planet frequency around these donor stars, but rather the planet frequency around the accretor. Specifically, the frequency of planets around the MS star in MS-WD systems should be compared with the planet frequency around either MS stars in MS-MS systems; similarly, the planet frequency around the WDs in WD-WD systems should be compared with planet frequency around the WD in WD-MS systems.

revealed in some cases, e.g. WASP-18 planetary system; Hellier et al. 2009). Their typical composition is likely to show irregularities and be more peculiar and metal rich, relative to that of typical first generation planets.

The second generation protoplanetary disk in which second generation planets form does not have to be aligned with the original protostellar disk of the star and its rotation direction, but is more likely to be aligned with the binary orbit (but not necessarily; the accretion disk from the wind of a wide binary may form in a more arbitrary inclination).

Studies on the formation and stability of planets in circumbinary orbits (see Haghighipour 2009 for a review) suggest that they can form and survive in such systems. Recently, several circumbinary planets candidates have been found (Qian et al. 2009, 2010a,b; Lee et al. 2009), possibly confirming such theoretical expectations. Circumbinary second generation disks such as discussed above could therefore serve, in principle, as nurseries for the formation and evolution of second generation planets.

The evolution of second generation planets in circumstellar and circumbinary disk could be very different. In the following we highlight some important differences between the types of orbits possible for second generation planets, and the way in which these could serve as a smoking gun signature for the effects and evolution of second generation planets and/or disks.

3.1. Orbital phase space of second generation planets

3.1.1. Circumstellar planets (around one of the binary components)

Stable circumstellar planetary systems in binaries could be limited to a close separation to their host star, since planets may be prohibited from forming at wider orbits or become unstable at such orbits which are more susceptible to the perturbations from the stellar binary companion (Haghighipour 2009, and references therein). During the post-MS evolution of a wide binary, its orbit typically widens (due to mass loss), therefore allowing for planets to form and survive at wider circumstellar orbits. This larger orbital phase space, however, is open only to second generation planets formed after the post-MS evolution of the binary (see also Thébault et al. 2009, for a somewhat related discussion on a dynamical evolution of such forbidden zone due to perturbations in a stellar cluster).

Let us illustrate this by a realistic example. Consider a MS binary with stellar components of 1.6 and 0.8 M_{\odot} and a separation of $a_b = 12$ AU on a an orbit of 0.3 eccentricity. The secondary protoplanetary disk in this binary would be truncated at about 2-2.5 AU in

such a system (Artymowicz & Lubow 1994), and a planetary orbit would become unstable at similar separations (Holman & Wiegert 1999). Specifically, Holman & Wiegert find

$$c_1 = a_c/a_b = (0.464 \pm 0.006) + (-0.38 \pm 0.01)\mu + (-0.631 \pm 0.034)e_b + (0.586 \pm 0.061)\mu e_b + (0.15 \pm 0.041)e_b^2 + (-0.198 \pm 0.047)\mu e_b^2, \quad (2)$$

where a_c is critical semi major axis at which the orbit is still stable, $\mu = M_2/(M_1 + M_2)$, a_b and e_b are the semi major axis and eccentricity of the binary, and M_1 and M_2 are the masses of the primary and secondary stars, respectively. Giant planets are not likely to form in such a system, since such planets are thought to form far from their host star (although they may migrate later on to much smaller separations, e.g. forming hot Jupiters), where icy material is available for the initial growth of their planetary embryos (Pollack et al. 1996). In fact, it is not clear if any type of planet could form under such hostile conditions in which strong disk heating is induced by perturbations from the stellar companion. The smallest binary separations in which planets could form are thought to be ~ 20 AU for giant planets (Haghighipour 2009, and references therein), although some simulations suggest that terrestrial planets may form even in closer systems, near the host star (up to $\sim 0.2q_b$, where q_b is the stellar binary pericentre distance; Quintana et al. 2007). Indeed the smallest separation observed for planet hosting MS binaries is of ~ 20 AU. We can conclude that first generation circumstellar giant planets are not likely to form in the binary system considered here. In our example the pericentre distance of the initial system is $q = a_b(1 - e) = 8.4$ AU, i.e. planets, and especially gas giants, are not likely to form in such system.

Back to our example, at a later epoch, the more massive stellar component in this system evolves off the main sequence to end its life as a WD of $\sim 0.65 M_\odot$ (see e.g. Lagrange et al. 2006). Due to the adiabatic mass loss from the system it may evolve to a larger final separation, given by (e.g. Lagrange et al. 2006, and references therein)

$$a_f = \frac{m_i}{m_f} a_i, \quad (3)$$

where $m_f (= 0.8 + 0.65 = 1.45 M_\odot)$ is the final mass of the system after its evolution, and $m_i (= 1.6 + 0.8 = 2.4 M_\odot)$ and $a_i (= a_b = 12 \text{ AU})$ are the initial mass and separation of the system, respectively (where the eccentricity does not change in this case). We now find $a_f = 2.4/1.45 a_i = 19.8 \text{ AU}$ [more detailed calculations we made, using the binary evolution code by Hurley et al. (2002) give a similar scenario]. At such a separation even circumstellar giant planets could now form in the system (Kley & Nelson 2008), i.e. second generation planets could form in this binary either at a few AU around the star, or closer if they

migrated after their formation). Therefore, any circumstellar giant planet observed around the MS star in this system would imply that such a planet must be a second generation planet, since it could not have formed as a first generation planet in the pre-evolved system. Thus, such cases could serve as a smoking gun signature and a unique tracer for the existence and identification of second generation planets. In fact, the example chose here is not arbitrary. The final configuration of the system in this example is very similar to that of the planetary system observed in the WD binary system Gl 86. A giant planet of $4 M_{Jup}$ have been found at ~ 0.1 AU from its MS host star, which has a WD companion, at a separation of ~ 18 AU (Mugrauer & Neuhauser 2005; Lagrange et al. 2006). The configuration of this system possibly indicates that this system is indeed a Bone fide second generation planetary system (see also section 7) .

In Fig. 2a (left), we use more detailed stellar evolution calculations (using the binary stellar evolution code BSE; Hurley et al. 2002) to show a range of final vs. initial semi-major axis of circular binary systems with initial masses $M_1 = 0.8 M_\odot$ and $M_2 = 1.6 M_\odot$ in which the higher mass star evolves to become a WD (of mass $\sim 0.6 M_\odot$). Also shown in this figure is the critical semi-major axis a_c in both the initial (pre-evolved MS-MS binary) and the final (evolved; MS-WD binary) configuration. As can be seen, the pre and post evolution critical semi-major axis differ significantly, presenting a region of orbital phase space open only to second generation planets but forbidden for first generation ones.

3.1.2. Circumbinary planets

In a sense, the requirements from a stable circumbinary planetary system present a mirror image of those needed for a circumstellar system in a binary. The orbital separation of circumbinary planets should be typically a few ($\sim 2-4$) times the binary separation (Holman & Wiegert 1999; Moriwaki & Nakagawa 2004; Pierens & Nelson 2007, 2008; Haghighipour 2009), in order not to be perturbed by the binary orbit. Specifically, Holman & Wiegert find

$$\begin{aligned} c_2 = a_c/a_b = & (1.6 \pm 0.04) + (5.1 \pm 0.05)e_b + (4.12 \pm 0.09)\mu + \\ & (-2.22 \pm 0.11)e_b + (-4.27 \pm 0.17)e_b\mu \\ & + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)e_b^2\mu^2, + \\ & (-4.27 \pm 0.17)e_b\mu + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)e_b^2\mu^2 \quad (4) \end{aligned}$$

where a_c is critical semi major axis at which the orbit is still stable, $\mu = M_2/(M_1 + M_2)$, a_b and e_b are the semi major axis and eccentricity of the binary, and M_1 and M_2 are the

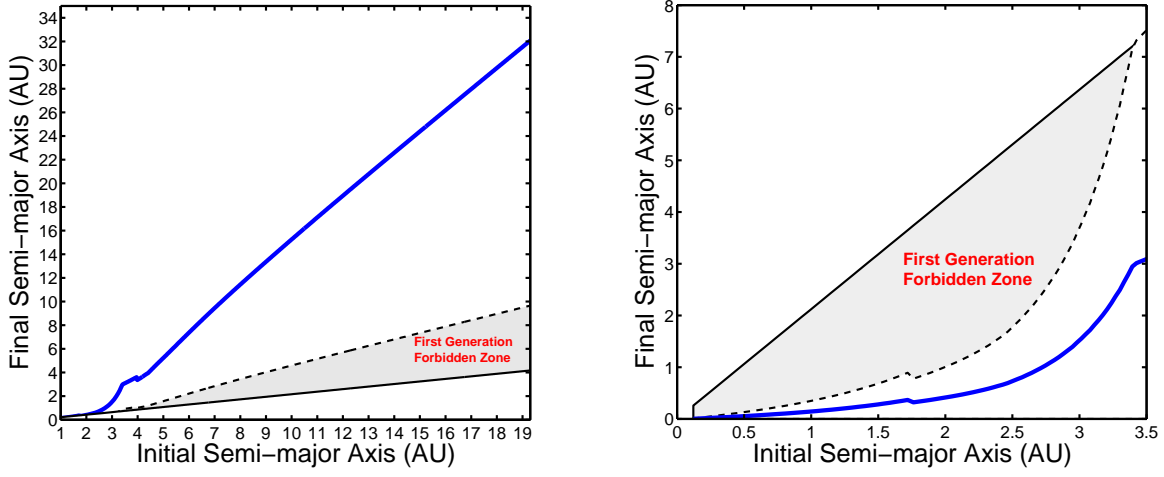


Fig. 2.— [left (a)] The configuration of evolved binary systems vs. their pre-evolved configuration. The pre-evolved binary is a MS-MS binary on a circular orbit with component masses $M_1 = 0.8 M_\odot$ and $M_2 = 1.6 M_\odot$, and the evolved binary is a MS-WD binary on a circular orbit with component masses $M_1 = 0.8 M_\odot$ and $M_2 = 0.6 M_\odot$. Solid thick line shows the final semi-major axis of binary systems vs. their initial, pre-evolved, semi-major axis. Solid thin line shows the critical semi-major axis a_c below which circumstellar planetary orbits around M_2 are stable in the pre-evolved MS-MS system. Dashed line shows the critical semi-major axis a_c below which circumstellar planetary orbits around M_2 are stable in the evolved MS-WD system. The region between these lines is forbidden for first generation planetary orbits in the pre-evolved system, but allowed for second generation orbits in the evolved system. [right (b)]. Similar to left figure, but showing a binary with a circumbinary disk. Solid thin line shows the critical semi-major axis a_c above which circumbinary planetary orbits are stable in the pre-evolved MS-MS system. Dashed line shows the critical semi-major axis a_c above which circumstellar planetary orbits are stable in the evolved MS-WD system. The region between these lines is forbidden for first generation planetary orbits in the pre-evolved system, but allowed for second generation orbits in the evolved system.

masses of the primary and secondary stars, respectively. Circumbinary planets are therefore not expected to be observed very close to their host stars. As with circumstellar second generation planets, the orbital phase space available for second generation planets differs from that of pre-existing first generation stars. The post-MS orbit of a relatively pre-evolved close binary (e.g. separation of 1-2 AU) could be shrunk through its evolution due to angular momentum loss in a common envelope or circumbinary disk phase [e.g. Ritter (2008) in the context of forming cataclysmic variables]. Second generation planets could therefore form much closer to such evolved binaries than any pre-existing first generation planets. Therefore, similar to the circumstellar case (but now looking on inward migration of the binary), circumbinary planetary systems observed to have relatively close orbits around their evolved host binary would point to their second generation origin. As described below (section 7), such candidate planetary systems have been recently observed. We note, however, that a caveat for such an argument is that pre-existing first generation planets, if they survive the post-MS evolution, could migrate inward (together with the binary, or independently) in the second generation disk. Nevertheless, even the latter case would reflect the existence and importance of a second generation protoplanetary disk and its interaction with first generation planets, as briefly discussed in the next section. Whether such inward migration is a likely consequence presents an interesting question for further studies.

Fig. 2b (right), is similar to Fig. 2a, but now showing the critical semi-major axis a_c for a circumbinary orbit in both the initial (pre-evolved MS-MS binary) and the final (evolved; MS-WD binary) configuration. Again, the pre and post evolution critical semi-major axis differ significantly, presenting a region of orbital phase space open only to second generation planets but forbidden for first generation ones.

We note in passing, that even non-evolved (low mass) MS close binaries with orbits of a few days were most likely evolved from wider binaries in triple systems, that shrunk to their current orbit due to the processes of Kozai cycles and tidal friction (Mazeh & Shaham 1979; Eggleton & Kisseleva-Eggleton 2006; Tokovinin et al. 2006; Fabrycky & Tremaine 2007). Formation of circumbinary close planetary systems even around short period MS binaries is therefore likely to be dynamically excluded, or would require a complicated and fine tuned dynamical history. Similarly, existence of close planetary systems around blue straggler stars, which were likely formed through similar processes (Perets & Fabrycky 2009) is also unlikely.

4. The fate of first generation planets and planetesimals in evolved binary systems

The fate of planets orbiting evolved planets have been studied before (Villaver & Livio 2007, 2009). Here we focus on the evolutionary routes unique for evolved binaries. A planet in such a system could orbit the evolving star, its companion or both. We shall first discuss the implication for the dynamical evolution of a planet due to mass loss in the system, more important for planets orbiting the mass transferring component and for circumbinary planets, then we'll discuss the possible implications for the interaction of the planet with the newly formed mass-transfer disk.

4.1. Dynamical evolution of planetary orbits due to mass loss

As discussed in section 3.1, due to the adiabatic mass loss from a binary/planetary system it may evolve to a larger final separation, as given by Eq. 3, keeping it's eccentricity, where we consider only planets far enough from their host evolving star (beyond the effects of gas drag in its expanding envelope; the outcomes of this latter possibility are discussed in the context of planets orbiting a single evolving star; Villaver & Livio 2007, 2009).

4.1.1. Circumstellar planets

Although the orbits of both the stellar companion and the circumstellar planet that orbit the mass-losing star evolve due to mass loss, their orbital evolution is quite different. The relative mass loss in each of these system differs, and therefore the change in the orbits differs too. The change to the circumstellar planet orbit is much larger than the change of in the stellar binary orbit, i.e. following Eq. 3

$$\frac{a_{p,f}}{a_{p,i}} = \frac{m_i}{m_f} = \frac{m_{1,i} + m_p}{m_{1,f} + m_p} \simeq \frac{m_{1,i}}{m_{1,f}} \gg \frac{m_{1,i} + m_2}{m_{1,f} + m_2} = \frac{a_{2,f}}{a_{2,i}}, \quad (5)$$

where the subscripts correspond to the system components (1, 2 and p for the evolving star, it's stellar companion and it's planetary companion, respectively), and the evolutionary stage of the system (i and f corresponding to the initial pre-evolved system, and the final post-mass loss WD system, respectively). The ratio between the semi-major axis of the stellar companion therefore changes accordingly, and always increases, by a factor of

$$\left(\frac{a_{p,f}}{a_{2,f}} \right) / \left(\frac{a_{p,i}}{a_{2,i}} \right) = \left(\frac{m_{1,i}}{m_{1,f}} \right) \left(\frac{m_{1,f} + m_2}{m_{1,i} + m_2} \right). \quad (6)$$

In some cases such an increase could make the planetary system unstable. Combining Eq. 2 with Eq. 6 gives us a general evolutionary stability criteria for pre-evolved circumstellar planetary systems that would survive the mass-loss stage in an evolved binary system (replacing a_c/a_b by $a_{p,f}/a_{2,f}$)

$$\left(\frac{m_{1,i}}{m_{1,f}}\right) \left(\frac{m_{1,f} + m_2}{m_{1,i} + m_2}\right) \left(\frac{a_{p,i}}{a_{2,i}}\right) < c_1, \quad (7)$$

where μ is defined as before, using the final masses $\mu = m_2/(m_{1,f} + m_2)$.

Systems which violate the evolutionary stability criteria are expected to become unstable. The planet in such systems is likely to be either ejected from the system or collide with one of the stars. Binary stellar evolution therefore guarantees the ejection of planets in some cases and the formation of free-floating planets population. More exotic outcomes could be the scattering of the planet into a circumbinary orbit or its exchange between its original host and the second stellar companion. These latter scenarios, however, would likely require some energy dissipation mechanisms to make such orbits stable on the long term (perturbation from an external flyby of a star or tidal dissipation through a close encounter with the second companion could serve as such mechanisms for these two scenarios, respectively). Note that these scenarios are not restricted only to planets in evolved binaries, and could be possible in planetary systems hosted by binaries, where the planets are ejected through planet-planet scattering (e.g. Marzari et al. 2005). The relative migration of the planet and the binary stellar companion in evolved binaries may also produce resonant interactions, similar, but with a greater amplitude, to asteroids and Kuiper belt objects in the Solar system, thought to evolve resonantly due to planet migration. These complex issues are beyond the scope of this paper, and will be explored elsewhere.

4.1.2. Circumbinary planets

This case is simpler than that of a circumstellar planet, since both the orbits of the planetary companion and the stellar companion change in the same way, i.e. $a_{p,f}/a_{p,i} = a_{2,f}/a_{2,i}$. Nevertheless, the stability criteria given in Eq. 4 still changes due to mass loss because, because of its dependence on the mass ratio of the binary components which changes during the process. An evolutionary stability criteria in this case is just given by Eq. 4 where again $\mu = m_2/(m_{1,f} + m_2)$. This criteria, however, does not take into account islands of instability even beyond the critical stability separation (Holman & Wiegert 1999), which happen at mean motion resonances. For this reason, the differential migration process may drive the system through such resonances producing unstable configuration even inside the

stability region. Again, these complex issues are beyond the scope of this paper, and will be explored elsewhere.

4.2. First generation planets in second generation disks

The evolution of a planet orbiting the companion star could be quite different than that orbiting the evolving star. The orbit of such a planet is not directly affected by the mass loss from the companion. However, in this case, the existence of a second generation disk reborn from the mass transfer could interact with such pre-existing first generation planets. Such planetesimals and/or planets could serve as “seeds” for a much more rapid growth of second generation planets. In this case second generation planet formation might behave quite differently than regular planet formation, suggesting a stage where large planetesimals and planets co-exist with and are embedded in a large amount of gaseous material. The first generation planets and planetesimals could now go through an epoch of regrowth (rejuvenation) through accretion of the replenished material. First generation planets may therefore grow to become much more massive than typical planets. Moreover, such planetary seeds could induce a more efficient planet formation and produce more massive planets on higher eccentricity orbits (Armitage & Hansen 1999). A possible observational signature of these planets could therefore be their relative larger masses, and possibly higher eccentricity. Whether such regrowth could even lead to a core accretion formation of exceptionally massive planets, effectively becoming brown dwarfs (in this case such brown dwarfs could now form much more often in the so called brown dwarf desert regime), is an interesting possibility.

We note on passing that in newly formed young binaries late infall of material from the protostellar disk of one star to its companion (the protoplanetary disk of one star may form earlier than that of its companion), may drive similar processes. Such a possibility could explain the existence of more massive close in planets in planet hosting binary systems. If protoplanetary disks preferentially form earlier around either the more massive component or around the secondary, than more massive close in planets should preferentially form around these preferred components, providing an observational signature for this process. In such regrowth scenarios, more massive planets are likely to form in binaries with closer separation, which could typically form more massive disks.

The replenished gas may also drive a new epoch of planetary migration. Together with the change in planetary masses and/or the formation of additional new planets in the system, the previously steady configuration of the planetary systems may now dynamically evolve into a new configuration. In multiplanetary systems such late dynamical reconfiguration

could lead to ejection of planets (free floating planets) and planetesimals from the system as well as to inward migration and/or possibly infall into their host stars. Alternatively these could still be bound to the binary system, in which case further interactions with either the original host star or the companion would produce a more complicated dynamical history, similar to the scenarios for unstable planets discussed in 4.1.

Given the possible misalignment between the second generation disk and the pre-existing planetary system, unique disk-planets configurations could be produced. Planets misaligned with the gaseous disk may both affect the disk through warping, and could be affected by it (Marzari & Nelson 2009). Small relative inclinations are likely to be damped through the planets interactions with the disk, re-aligning the planets (Cresswell et al. 2007). Observations of two co-existing misaligned planetary systems or even counter rotating planets in the same system could, in principle, serve as a spectacular example of second generation planetary formation with pre-existing first generation planets. However, dynamical interactions in multiplanetary systems could possibly produce somewhat similar effects, although likely not the counter rotating configurations (Chatterjee et al. 2008; Jurić & Tremaine 2008).

5. Second/third generation planets formation around compact objects and evolved stars

Few planetary systems and debris disks have been found to exist around compact objects, such as the pulsar planets (Wolszczan & Frail 1992), debris disks around the neutron star (Wang et al. 2006), planets around evolved stars (Silvotti et al. 2007; Lee et al. 2009) and the possible planets observed around WDs (Qian et al. 2009, 2010a,b). These systems are generally thought to either form in a fall back disk of material following the post-MS evolution of the progenitor star (e.g. fall back material from a supernova; Lin et al. 1991, but see also Livio et al. 1992); or form around the MS star and survive the post-MS evolution stage of the star.

Mass transfer in binaries poses an alternative and robust way of providing disk material to compact objects. Second (or possibly third) generation planets could therefore naturally form around many compact objects, and should typically exist around compact objects in doubly compact binary systems. Such systems may show differences relative to planets formed around MS stars due to the quite different radiation from the hosting (compact) star, as well as the difference of their magnetic fields. Some studies explored planet formation around neutron stars (see Sigurdsson et al. 2008, for a recent review) and WDs (Livio et al. 1992), but these issues and the issue of binarity in these systems are yet to be studied in more depth. In this context Tavani & Brookshaw (1992); Banit et al. (1993) made some

pioneering efforts relating to planet formation in NS binaries, although focusing on pulsar planets and the evaporation of stellar companion to the NS as a source for protoplanetary disk material. Much more directly related are the studies done later by Livio et al. (1992) and Beer et al. (2004) in order to explain the pulsar planet PSR B1620-26 (see section 7).

This alternative scenario for the formation of planetary systems around compact objects suggests a different interpretation for planets in compact object system; observations of such planetary systems might not reflect the survival of planets through post-MS evolution of their host star, but rather their formation at even a later stage from the ashes of a companion star. Such systems (e.g. Schmidt et al. 2005; Maxted et al. 2006; Silvotti et al. 2007; Geier et al. 2009) should therefore be targets for searches of compact object companions. Note, however, that formation of sdB stars may require the existence of a close companion (see Heber 2009, and references therein), such as these observed planets. This, in turn, would suggest that a planet have already been in place prior to the sdB star formation in these systems.

6. Observational expectations

From the above discussion we can try to summarize and formulate basic expectations regarding second generations planetary systems and their host stars. These could serve both to identify the second generation origin of observed planetary systems and to provide guidelines and directions for targeted searches for second generation planets.

1. Second generation planets should exist in evolved binary systems, most frequently in WD-MS or WD-WD binaries. Such systems should therefore be the prime targets for second generation planetary systems searches. Since WD binaries are relatively frequent (Holberg 2009), second generation planets could be a frequent phenomena (with the caution that our current understanding of planet formation, especially in such systems, is still very limited). Evolved binary systems may show a different frequency of hosting planetary systems (around the MS star in a binary MS-WD systems) than MS binaries with similar orbital properties. Planet hosting compact objects are more likely to be part of double compact object binaries rather than be singles.
2. The host binaries separation are likely to be between 20 AU to 200 AU for binaries hosting circumstellar planets, and up to a few AU for binaries hosting circumbinary planets.
3. Planets in post-MS binaries could reside in orbital phase space regions inaccessible to pre-existing first generation planets in such systems (section 3.1). Observations of

planets in such orbits could serve as a smoking-gun signature of their second generation origin.

4. Second generation planets could form even around metal poor stars and/or in metal poor environments such as globular clusters; planetary systems in such environment are likely to be part of evolved binary systems.
5. Planets showing age inconsistency with (i.e. being younger than) their parent host star could be possible second generation planets candidates. In such systems one may therefore search for a compact object companion to the host star.
6. Stars in WD binaries showing evidence for mass accretion from a companion star (e.g. chemically peculiar stars such as Barium and CH stars) could be more prone to have second generation planetary companions (for adequate binary separations)
7. Second generation planets could be more massive than regular exo-planets. This may be suggestive that old planet hosting stars with extremely massive planets (or brown dwarf companions found in the brown dwarf desert) are more likely to be second generation planetary systems. Again this could point to the existence of a compact object (most likely WD) companion at the appropriate separations.
8. Planets around compact objects could be second generation planets from mass transfer accretion. These systems are therefore more likely to have a compact object companion. Also, polluted WDs, thought to reflect accretion of asteroids, might be more likely to have WD companions.
9. The spin-orbit alignment between second generation planets and their host stars is likely to differ from that of first generation planets, and second generation planets might be more likely to show higher relative inclinations between different planets in multiple planetary system.
10. Statistical correlation between planetary companions and their host star metallicity could show a difference between WD binary systems and MS binary systems (but this may be a weak signature, given that the host star itself accretes metal rich material). Chemically peculiar stars in WD binaries may serve as good second generation planetary hosts candidates.
11. The MS stars in WD-MS binaries may also show higher rotational velocities, due to planetary infall, although such phenomena could also be induced by the re-accretion of matter from the second generation disk. In either case, stars with high rotational velocities in WD binaries could be better candidate hosts of second generation planets.

7. Candidate second generation planetary systems

Observationally, many post-AGB binary stars show evidence for having disks surrounding them either in circumstellar or circumbinary disks (Van Winckel 2004; de Ruyter et al. 2006; Hinkle et al. 2007; van Winckel et al. 2009). Such disks have many similarities with protoplanetary disks as observed in T-Tauri stars, suggesting that new generations of planets could form there (Ireland et al. 2007; Zuckerman et al. 2008; Melis et al. 2009). Nevertheless, only very few studies focused on this possibility. A specifically interesting case is the Mira AB system, studied by Ireland et al. (2007). Their observations and their interpretation suggest that a ~ 10 AU dusty disk have been formed in this system through mass-transfer, which have properties quite similar to those observed for protoplanetary disks around T-Tauri stars (in fact, it's observed spectrum is indistinguishable from that observed in some protoplanetary disks around T-Tauri stars; S. Andrews, priv. comm.).

As discussed above, there are several observational expectations for second generation planetary systems. Currently, several observed planetary systems and planetary candidates may be consistent with such expectations, and may therefore be considered as candidate second generation planets. These systems are found in evolved binary systems, and include both circumstellar planets such as in GL 86 (Queloz et al. 2000; Lagrange et al. 2006; Mugrauer & Neuhäuser 2005) and HD 27442 (Mugrauer et al. 2007) as well as the circumbinary planet in PSR B1620-26 (Backer et al. 1993), and circumbinary planet candidates: HW Vir (Lee et al. 2009), NN Ser (Qian et al. 2009) and DP Leo (Qian et al. 2010b); the latter candidates, however, may not be actual planetary systems (Parsons et al. 2010). These systems are consistent with being second generation planetary systems, as their host binary separation is the region where second generation disks could be formed.

Interestingly, according to Lagrange et al. (2006) the planetary orbit of GL 86 could have been in the forbidden region for first generation planets (i.e. where they could have not formed and survived) for the most plausible parameters for the WD progenitor in this system, which are consistent with its cooling age (Lagrange et al. 2006; Desidera & Barbieri 2007). Although this discrepancy could possibly be circumvented by taking different age and mass estimates for the progenitor, under some assumptions (Desidera & Barbieri 2007), a second generation origin for this planet presents an alternative simple and natural explanation. Besides its consistency with being a second generation planet, GL 86 may therefore show the smoking gun signature of a second generation planetary system.

Similarly the circumbinary planets candidates in HW Vir, NN Ser and DP Leo are found to be in regions likely to be inaccessible or less favorable for first generation planets in the progenitor pre-evolved binary systems. These planets orbit their evolved binary host at separations of only a few AU, where the pre-stellar evolution orbits of these binaries might

have as wide as a few AU (e.g. Ritter 2008), i.e. these planets could not have formed in-situ as first generation planets in their current position. However, these orbits are accessible for in-situ formation of second generation planets in the already evolved and much shorter period binary observed today.

The globular cluster pulsar planet PSR B1620-26 (Backer et al. 1993) is another highly interesting second generation candidate. It is the only planet found in a globular cluster (metal poor environment) and it is a circumbinary planet around a WD-NS binary, found in the cluster outskirts of a globular cluster, as might be expected from our discussion above of second generation planets in globular clusters (see section 3). Several studies suggested scenarios for the formation of this system and its unique and puzzling configuration (Sigurdsson & Thorsett 2005; Sigurdsson et al. 2008). These usually require highly fine tuned and complex dynamical and evolutionary history. A second generation origin could give an alternative and more robust explanation [as also suggested by Livio & Pringle (2003) and studied by Beer et al. (2004)]. The high relative inclination observed for this planets suggested that even in the second generation scenario some an encounter with another star is required to explain this system (Beer et al. 2004). However, recent studies show that high inclinations could also occur from planet-planet scattering in a multiple planet system (Chatterjee et al. 2008; Jurić & Tremaine 2008). Note that the existence of another planet in this system is highly unlikely for the favorable formation scenarios discussed by Sigurdsson et al. (2008), but could be a natural consequence for the second generation scenario. This could motivate further observational study of this system. Similarly, findings of additional globular cluster planets preferably in WD binary systems would strongly support the second generation scenario origin of globular cluster planets (see also Sigurdsson & Thorsett 2005).

Other possibly weaker candidate second generation planets would be those planets found around metal poor stars (e.g. Santos et al. 2007). Finding a WD companions for such stars, however, would give a strong support for the second generation scenario and the identification of these systems as second generation planets.

We conclude that several second generation candidate planets have already been observed, and show properties consistent with the scenario discussed in this paper. Moreover, the current properties of these systems may pose problems for our current (poor) understanding of first generation planets formation and evolution in evolved binary systems, which could be naturally solved in the context of second generation planets. Observed WD-MS binary systems (e.g. Rebassa-Mansergas et al. 2009) should therefore serve as potentially promising targets for exo-planets searches.

8. Conclusions

In this paper we discussed the implications of binary stellar evolution on planetary systems formation and evolution. We raised the possibility for the formation of second generation planetary systems in mass transferring binaries as a possible route for planet formation in old evolved systems and around compact objects in double compact object binaries. We presented possible implications for this process and the planetary systems it could produce, and detailed the possible observational signatures of second generation planetary systems. We also pointed out a few currently observed planetary systems with properties suggestive of a second generation origin. In addition we discussed the orbital evolution of pre-existing planets in evolving binary systems due to mass loss from the system and the possible interaction with the formed accretion disk.

The possibility of second generation planets and the study of planets in evolved binary systems may open new horizons and suggest new approaches and targets for planetary searches and research. It suggests that stellar evolution processes and stellar deaths may serve as the cradle for the birth and/or rejuvenation of a new generation of planets, rather than being the death throes or hostile hosts for pre-existing planets. In particular such processes could provide new routes for the formation of habitable planets, opening the possibilities for their existence and discovery even in (the previously thought) less likely places to find them. The environments of old stars and more so of compact objects could be very different from that of young stars. Such different environments can strongly affect the formation of second generation planets and possibly introduce unique processes involved in their formation and evolution. The discovery and study of second generation planets could therefore shed new light on our understanding of both planet formation and binary evolution, and drive further research on the wide range of novel processes opened up by this possibility.

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